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ENERGY AND TECHNICAL PROGRESS

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January 1980

ABSTRACT

When we use the Cobb-Douglas equation to investigate economic growth, we require data on the levels of the capital and labor inputs, and corresponding data on the level of output, at different points in time. We conclude that the inclusion of energy in the standard Cobb-Douglas production function does not explain the contribution of technological process (Hicks-neutral) to a rise in the rate of output unless, possibly, one is able to make the seemingly unreasonable assumption that labor should not appear in the production function.

An interesting future project will be a statistical analysis of the historic trend in GNP, a technological change and the consumption of available energy.

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INTRODUCTION

Since 1925, when Cobb and Douglas introduced their aggregate production function,[1] economists have tried to explain the growth of the American economy by the growth of the factor inputs in such a production function. Historically, only the aggregate inputs of capital and labor were considered and the production function was written

$$Y = AK^{\alpha}L^{\beta}, \qquad (1)$$

where Y is national income, A a constant of proportionality, K some measure of the capital input (usually the gross or net capital stock), L the labor input, and α and β the output elasticities, respectively, of capital and labor.

The aggregate production function, in Cobb-Douglas form [Eq. (1)], along with consumption and investment functions etc., has long been used as one of the principal equations in macroeconomic models of the economy. In this paper, we will ignore demand. Equation (1) says that if the capital and labor inputs are given, output is uniquely determined.

When we use the Cobb-Douglas equation to investigate economic growth, we require data on the levels of the capital and labor inputs, and corresponding data on the level of output, at different points in time. In this way, we seek to explain changes in output by changes in inputs and to understand better what the exact relationship is. The problem is more complicated than it might appear at first glance.

There is a two-fold data problem. On the one hand, we are aggregating many different types of capital inputs, labor inputs, and the diverse outputs of the economy. On the other hand, we must be aware of the fact that there are substantial qualitative changes in the form of these inputs and outputs as we go backward or forward in time. Both of these problems have been the subjects of books and articles.

The point here is not to discuss and resolve them thoroughly, which might not be possible in any case, but simply to mention them as examples of the data problems that plague all the work in this field.

The labor input is measured by person-hours of labor per year, and each hour of each worker is treated as equal to each hour of every other worker. This method does not take account of the qualitative changes in the makeup of the work force, which are many. The age and sex breakdowns vary over time and affect productivity, e.g., older workers are likely to be more productive than younger workers. We also neglect, by our method, the effect of "human capital" formation on productivity. "Human capital" is formed when workers forge present earnings to invest time in school or training that will enable them to obtain higher wages in the future. Over the period 1929-1969, from which our data are taken, the average level of educational attainment was increasing, in general, in the U.S. We should suspect that this trend affects the relative value of an average input man-hour in different years.

The dollar value of the capital stock is usually used as a proxy for the capital input. Two series for the value of the aggregate capital stock are generally calculated by the statisticians: one consists of the purchase prices of all capital in service in year t, called the gross capital stock in year t; the other consists of the sum of the values of all the different pieces of capital in year t after allowance has been made for yearly depreciation and is called the net capital stock in year t. These values for total capital stock must be considered approximate at best. Constant dollars are used in order to try to put all the data on a uniform footing. The use of the aggregate capital stock as a proxy for the capital input is somewhat suspect, but defining what exactly does constitute the true capital input is a serious problem. If we want to be strict, production machinery can be considered an input only when it is actually in use. The walls of a building, on the other hand, provide a constant sheltering service to whatever is inside that building and should be evaluated differently. There are an infinite number of different type of capital goods that fall between the above two extremes; the problem of defining a truly satisfactory capital input number seems insoluble. If it were not impossible, the empirical data problem surely would be.

It is clear that some sweeping assumptions have to be made in the acceptance of some definition of the capital input. We must first distinguish between a change in the capital input arising from an addition to or retirement from the stock, and a change in the capital input owing to greater or lesser use of the existing stock. One assumption we will make is that the stock of capital is used evenly. We assume that each discrete unit comprising the total stock has a "normal" rate of utilization. This "normal" rate can be left undefined; it will be used only in a relative sense. If we assume the aggregate stock to be in a "normal" state of utilization, and then assume a 5% increase in the aggregate capital input, with no additions to the stock proper, we mean that each discrete unit of capital is being used at a rate 5% greater than "normal." Although this prescription is undoubtedly incorrect, it is at least a step toward clarifying what we mean by "capital input." We need not define a "normal" rate of usage since our method uses an index number for the data. We will assume that deviations from normal usage of the capital stock are reflected in labor force employment rates. While there is surely a correlation between the rate of employment of the labor force and that of the capital stock, there is no telling how great or small this correlation may be. Therefore, with tongue firmly in cheek, we multiplied our capital stock indices by the labor force employment rate to arrive at a capital input index. We should add that Solow applied a similar correction in his path-breaking work in this area.[2]

TECHNICAL PROGRESS

Past work has often assumed that the Cobb-Douglas aggregate production function exhibits constant returns to scale; i.e., it is homogenous of degree one. This means that the exponent, α and β, should sum to one. The advantage of this prescription, theoretically, is that the function is homothetic; the marginal rate of factor substitution remains unchanged when the input factor quantities are multiplied by any scalar. Theory tells us that the output elasticities of capital and labor [the exponents α and β in Eq. (1)] should be equal to the fractions of the national income earned by capital and labor, respectively. Over the last century, labor's share of national income has stood between 2/3 and 3/4, with capital holders receiving the remainder. In order to test how well our data from 1929 to 1966 fit the constant returns to scale and factor share assumptions, we regressed Eq. (1), in log-linear form (see the methodology section), without imposing any a priori constraints on α and β. Ordinary least-squares regression gave values of $\alpha = 0.234$ and $\beta = 0.852$. These sum to 1.086, indicating increasing returns to scale, and puts the distributive shares at 0.785 for labor, 0.215 for capital.

Graphically, a production function with increasing returns to scale has an increasing slope. Figure 1 illustrates a one-factor production function with increasing returns to scale. Some hypothetical data points are included.

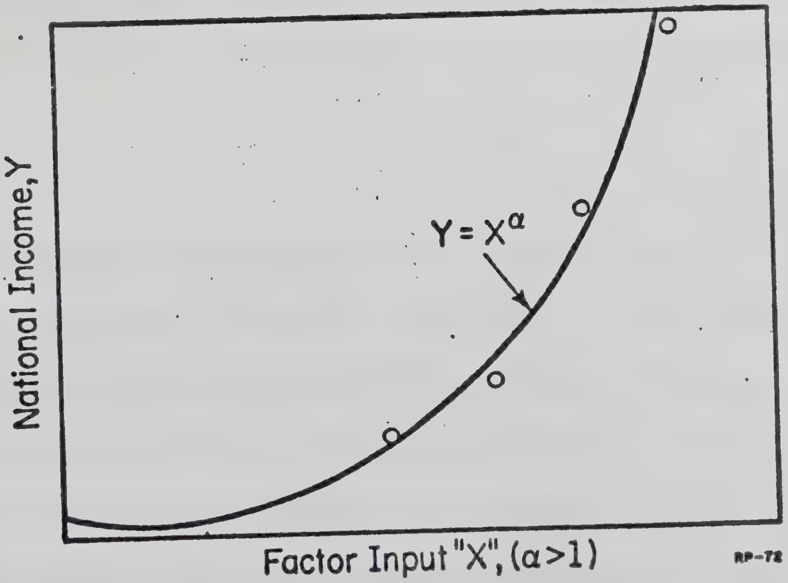

Figure 1. Increasing returns to scale.

Equation (1) has no time dependence. Equal amounts of capital and labor in any two years should produce equal amounts of output. Over any span of years, the quality of capital goods and that of consumer goods and services, and of the labor force, changes considerably. Technical innovation and changing consumer preferences are constantly altering the forms of these goods and services so that they are not strictly comparable over time. As mentioned before, the qualities that describe the aggregate labor force are also changing over time so that not even the unit of labor input (i.e., the man-hour) will measure the same thing in diverse years. Taken together, these forces give rise to another almost insurmountable data problem.

This is one of the reasons for which theorists have suggested including some sort of time dependence in the aggregate production function. The usual method for achieving this is to add an exponential time term, of the form† e^{rt}, to the function. With this addition (and subscripts on the variables to indicate year 5), Eq. (1) becomes

$$Y_t = Ae^{rt}K_t^{\alpha}L_t^{\beta} \quad . \tag{2}$$

The variable r is now interpreted as the rate of increase of technical progress, where technical progress is broadly defined to include anything that augments output without changing the quantity of capital or labor.

An exponential technical progress term has the effect of shifting the entire production function upward each year by a constant factor. Using the same data we used in regressing Eq. (1), where we found increasing returns to scale, we regressed Eq. (2), again in log-linear form. The results were $\alpha = 3.04$, $\beta = 0.692$, and $r = 0.0138$.

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†We also tried $Y_t = AtK_t^{\alpha}L_t^{\beta}$ and $Y_t = At^{\gamma}K_t^{\alpha}L_t^{\beta}$; these gave inferior statistical fits.

We now have $\alpha + \beta = 0.996$ (this was not statistically different from $\alpha + \beta = 1$) and a rate of increase of technical know-how of 1.38% per year.

Technical progress has always been difficult for economists to explain fully. It is not a physical quantity that can be measured explicitly, but it can be defined strictly as follows. Given two points in time t_o and t_1, with t_1 later than t_o, there has been technical progress over the period $[t_o, t_1]$ if it is possible to produce a greater quantity of output at t_1 than was possible at t_o, with identical factor inputs at both times. Mathematically, we write a production function $y = F(\bar{x}, t)$ with $\bar{x}$ a vector of factor inputs, time coordinate 5 and physical output y. We have had technical progress from t_o to t_1 if $y_1 = F(\bar{x}, t_1) > y_o = F(\bar{x}, t_o)$. The chief discussion, in the past, has been over the question of the neutrality of technical progress. Was technical progress embodied in new capital, or in the changing makeup of the labor supply, or was it (Hicks) neutral, continuing to increase output without changing the actual capital stock or the labor force? Solow, in an early article on the subject,[2] found that technical progress was essentially neutral; more important, he attributed 7/8 of the growth rate in GNP to technical progress and only 1/8 to increases in the capital and labor inputs. This last result is extraordinary: economic growth cannot be well explained by increases in the capital stock and the labor force; we must instead resort to a mysterious concept that we call "technical progress."

In 1963, Nelson[3] investigated this problem, using data series running from 1929 to 1960. Table 1 is constructed from data taken from his paper.

TABLE 1.

HISTORICAL GROWTH RATES OF OUTPUT, LABOR FORCE,
CAPITAL, AND TECHNICAL PROGRESS.
(From Ref. 3)

Year	Potential GNP	Potential Man-Hours	Gross Capital Stock	Technical Progress r (β = .75)	Technical Progress r (β = .5)
1929-1960	3.1	0.7	2.0	2.1	1.7
1929-1947	2.5	0.5	1.0	1.9	1.7
1947-1960	4.0	0.8	3.6	2.5	1.8
1947-1954	4.4	0.7	4.0	2.9	2.1
1954-1960	3.5	0.8	3.1	2.1	1.6

Nelson tried to correct for variations in the level of business activity by appealing to the concepts of "potential GNP," and "potential man-hours." These items are defined and discussed by Okun in his 1962 paper.[4] Nelson did not regress his data to chose α and β, the capital and labor output elasticities. Instead, he specified them as $\beta = 0.75$, which is about what we would expect from looking at the national income accounts, and $\beta = 0.5$, which he tries simply as a sensitivity test of the results. These assumptions, when combined with a constant returns to scale assumption, also specify α and make the estimation of r a simple matter.

ENERGY

The central question which we tried to examine in this paper was the connection between energy consumption and technical progress. Fossil fuel energy has become totally indispensable to the modern industrial economy, as necessary for production as machinery or labor. In addition, the level of energy consumption has been increasing exponentially since the industrial revolution, and has totally altered the ways in which we live and work. Empirical work has indicated that, in the aggregate, energy may be a substitute for labor and capital in production. In the short run, aggregate energy and capital are complements, but in the long run they can substitute.[5]

Mineral reserves, including energy, are of course finite. What distinguishes fossil fuels from the other raw material resources is that they can be used but once. After a fuel is burned, it is gone forever, whereas metals can be reused over and over again, if enough energy is at hand to reforge them.

We do not think that previous investigators have handled the question of a connection between energy use and technical progress. Solow includes the value of mineral reserves in his capital stock, but this does not really measure the extent of the energy *input* to the economy. Nelson uses as his capital stock the value of all reproducible capital, which clearly excludes energy. The true fossil fuel input is that amount that is extracted and consumed each year. Both Nelson's and Solow's methods assume implicitly that fuels will always be available as an economic good. If this assumption is wrong, the theory should be altered accordingly. It may be that the earth's fossil fuel reserves will be able to supply us into the distant future. If this is in fact true, there is no quarrel with Solow's or Nelson's method.

Recently, there has been some conjecture that we really are in danger of running short of accessible fuels. It is only in this case that the previous work needs re-examination. The question of interest becomes the following: Does the rate of technical progress, r, change when fossil fuels are put into the production function? If there is a reduction in r when fossil fuels are included, we might conclude that a scarcity of fuels in the future might cause a reduction in the rate of technical progress.

In order to try to answer this question, we included an energy input explicitly in a Cobb-Douglas type production function. If increased energy consumption was behind some of what we call technical progress, the value of r, the technical progress term, should be less than its value in the non-energy-inclusive production function.

METHODOLOGY

In order to run a regression, we must put our production function [Eq. (2)] into the proper form for econometric analysis. We include a random disturbance term, w_t, with mean one and finite variance, in

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Berndt and Wood[11] assumed a translog cost function and determined the factor cost shares the tendency for substitution or complimentarity between capital, labor, energy and materials from 1947 to 1971.

our function, which becomes.

$$Y_t = Ae^{rt}K_t^{\alpha}L_t^{\beta}w_t \quad . \qquad (3)$$

Taking logarithms gives

$$\ln Y_t = \ln A + r^t + \alpha \ln K_t + \beta \ln L_t + \ln w_t \qquad (4)$$

We define $\ln w_t = u_t$ so that u_t has mean zero and finite variance, while

$$\ln Y_t = \ln A + r^t + \alpha \ln K_t + \beta \ln L_t + u_t \qquad (5)$$

Equation (5) is in the proper form for least-squares regression. In several of our runs, we added another term such as $\gamma \ln E$ where E was energy input or $\gamma \ln [El]$ with [El] the electricity input. For all of our time series, we indexed the initial year's value to 100 before taking logarithms. The computer program that we used in all of our least-squares regressions gives estimates of the values of all the unknown coefficients, along with estimates of their variances. In addition, a t-statistic is calculated, which measures the probability that a given coefficient is different from zero. The r^2 statistic is a measure of how well the estimated model explains the observed data. All of the regressions gave values for "A" that were statistically indistinguishable from one. No more need be said here about "A."

THE ENERGY-INCLUSIVE MODELS

Two different methods for including energy in a production function were tried. The first method treats the energy flow into the economy as part of the total capital input. We created a time series with which we attempt to measure the absolute value of the yearly input of reproducible capital and added to it the value of energy consumed in each year. In constructing our time series for the input of physical capital alone (as we mentioned in the introduction), we avoided the problem of determining an absolute level of capital input. If we want to combine capital and energy into a single "value of capital/energy" input this is no longer possible. We decided to use the amount of depreciation in the physical capital stock as an approximation of the absolute level of the physical capital input. This seems reasonable; physical depreciation is in some sense the actual input from the capital stock, and should vary in rough proportion to the amount of use that the stock undergoes.

In constructing this series, we combined Denison's data[6] for the net value of the reproducible capital stock with data on yearly investment as given in the appropriate columns in Ref. 7. The method will now be described. Defining K_t and K_{t+1} as the values of the net capital stock in the years t and t+1 and I_t as the amount of investment in year t, the depreciation D_t is given by

$$D_t = K_t + I_t - K_{t+1} . \qquad (6)$$

The ratio D_t/K_t was calculated for each of the years 1947-1964. The mean value of the ratio is 0.097 with a surprisingly small standard error (0.007). We therefore multiplied our "value of net capital stock" time series by 0.097 to form our capital input series.

Data on the value of all energy produced, i.e., the value of all fossil energy at the mine mouth or the well-head (plus value of net imports) are given in Ref. 8. Adding the value of energy and the value of the capital input gives a new time series that we can use to investigate the effect of energy on technical progress. Our new production function (again with random error term w_t) takes the form

$$Y_t = Ae^{rt}\,(K + E)_t^{\alpha} L_t^{\beta} w_t \ . \tag{7}$$

If increased energy consumption had been understating the input of capital to the economy, the estimated value of "r" in Eq. (7) should be lower than that found in Eq. (2).

The second method we used was the addition of an independent energy term to the two-factor capital-labor-energy production function. This is written as follows:

$$Y_t = Ae^{rt} K_t^{\alpha} L_t^{\beta} E_t^{\gamma} w_t \ . \tag{8}$$

The E_t time series that we used measure the quantity of energy consumption, in physical units. We also entertained the suspicion that increasing use of electricity might be more closely connected to technical progress than energy per se, so we tested the following capital-labor-electricity production function:

$$Y_t = Ae^{rt} K_t^{\alpha} L_t^{\beta} [El]_t^{\gamma} w_t \ . \tag{9}$$

The $[El]_t^{\gamma}$ time series is also in physical units and was indexed to 1929 = 100 (as all our data were), before logarithms were taken.

DATA

We required time series data on GNP, labor input, capital stock, total energy consumption (physical units and dollars), investment, and electricity consumption. In order to avoid the vagaries introduced by the war years and the depression, we used the years 1929, 1940, 1941, 1947 - 1969. Table 2 displays our data sources.

TABLE 2. Data sources.

GNP	Allen[9]
LABOR	Allen[9]
CAPITAL STOCK	Denison[6]
GROSS ENERGY	Sonenblum[8]
VALUE OF ENERGY	Sonenblum[8]
GROSS ELECTRICITY	Edison Electric Institute[10]
INVESTMENT	Survey of Current Business[11]

The data were indexed to 1929 = 100 and logarithms taken to put them into suitable regression form. Regression data are displayed in Table 3.

Table 3. Regression Input Data; all data (except time) are logarithms of indices with 1929 = 100.

Year	Time	GNP	Labor	Capital	Energy	Energy + Capital	Electricity
1929	1.0	4.605	4.605	4.605	4.605	4.605	4.605
1940	12.0	4.715	4.670	4.317	4.609	4.398	5.067
1941	13.0	4.864	4.786	4.407	4.708	4.503	5.230
1947	19.0	5.025	4.885	4.555	4.880	4.698	5.672
1948	20.0	5.069	4.908	4.633	4.905	4.826	5.772
1949	21.0	5.070	4.881	4.662	4.832	4.805	5.805
1950	22.0	5.162	4.919	4.728	4.908	4.881	5.926
1951	23.0	5.238	4.999	4.797	4.987	4.939	6.050
1952	24.0	5.268	5.021	4.842	4.979	4.971	6.125
1953	25.0	5.312	5.039	4.882	5.009	5.017	6.241
1954	26.0	5.298	5.006	4.890	4.973	5.012	6.306
1955	27.0	5.371	5.030	4.939	5.064	5.061	6.463
1956	28.0	5.390	5.053	4.986	5.113	5.105	6.562
1957	29.0	5.404	5.057	5.026	5.113	5.145	6.614
1958	30.0	5.392	5.028	5.030	5.113	5.081	6.633
1959	31.0	5.454	5.053	5.066	5.147	5.161	6.730
1960	32.0	5.479	5.070	5.094	5.180	5.183	6.816
1961	33.0	5.498	5.066	5.108	5.196	5.179	6.870
1962	34.0	5.634	5.094	5.146	5.241	5.233	6.944
1963	35.0	5.601	5.107	5.175	5.280	5.256	7.013
1964	36.0	5.654	5.129	5.216	5.319	5.285	7.084
1965	37.0	5.715	5.166	5.270	5.359	5.309	7.151
1966	38.0	5.779	5.215	5.335	5.415	5.388	7.237
1967	39.0	5.804	5.242	5.392	5.447	5.438	7.301
1968	40.0	5.850	5.270	5.444	5.506	5.481	7.384
1969	41.0	5.876	5.298	5.495	5.556	5.530	7.466

RESULTS

The results of our least squares estimations are shown in Table 4. Standard errors are displayed beneath the estimates of the coefficients.

Table 4. Results of regressions; standard errors are given in parentheses.

Equation Form	Values of the Coefficient				r^2 (statistic)
	r	α	β	γ	
a) $Y = AK^{\alpha}L^{\beta}$	-	.234 (.098)	.852 (.096)	-	.99495
b) $Y = Ae^{rt}K^{\alpha}L^{\beta}$	.0138 (.0004)	.304 (.045)	.692 (.041)	-	.99958
c) $Y = Ae^{rt}(K+E)^{\alpha}L^{\beta}$	.0133 (.0012)	1.383 (.072)	.610 (.068)	-	.99943
d) $Y = Ae^{rt}K^{\alpha}L^{\beta}E^{\gamma}$	.0130 (.0010)	.224 (.070)	.571 (.093)	.202 (.139)	.99962
e) $Y = Ae^{rt}K^{\alpha}L^{\beta}[E1]^{\gamma}$	.0131 (.0013)	.300 (.045)	.686 (.042)	.001 (.002)	.99959
f) $Y = Ae^{rt}K^{\alpha}E^{\gamma}$	.0084 (.0011)	.031 (.102)	-	.976 (.097)	.99895
g) $Y = Ae^{rt}L^{\beta}E^{\gamma}$	.0130 (.0012)	-	.440 (.098)	.550 (.102)	.99944
h) $Y = Ae^{rt}L^{\beta}[E1]^{\gamma}$	.0168 (.0021)	-	.948 (.025)	.002 (.003)	.99877
i) $Y = Ae^{rt}K^{\alpha}[E1]^{\gamma}$	.0002 (.0037)	.990 (.057)	-	.007 (.006)	.99464

Before we draw any conclusions from these results, an important fact about least squares regression must be noted. When we apply least squares to a model, we have already assumed that the model has been specified correctly. Errors in estimation (biased estimators) result when a relevant variable has been excluded. The addition of extraneous variables will not bias the estimators, or their estimated variances, provided the set of data points is infinite. If we have a finite set of data points and have included extraneous variables in our model, the variances of the coefficients of the variables that are relevant will be increased and the estimators for the irrelevant variables should be zero.

Our results cannot tell us which one of the models "a" through "i" of Table 4 is the correct one, but if one of them happens to be correct, the table gives the unbiased least-squares estimators. If we can narrow down the range of possible models to include only "b", "c", and "d", we can see that, no matter which one is correct technical progress increases at a rate of 1.3% per year. We can say that, whether or not energy consumption was a determinant of output, the rate of technical progress has had this constant value over the period 1929-1969.

If capital and labor inputs are taken as given, a scarcity of fossil-fuel inputs will not stop our production possibilities from increasing at 1.3% per year, if any of these three models is correct. If "c" or "d" is correct, a scarcity of fuel will limit the maximum production that we can attain but the production function as a whole will continue its steady upward shift.

As an extreme condition, we eliminated labor from the model and found that a capital-energy and especially a capital-electricity model (f and i) allowed an accurate estimate of production without a term for technical progress (this was not true for a labor-energy model). The standard error on some of the exponents was quite large, however. These results sharply point up the deficiencies of the production function approach to distributing shares of production. We have only personal judgment as to which variables should appear in the function.

We conclude that the inclusion of energy in the standard Cobb-Douglas production function does not explain the contribution of technological progress (Hicks-neutral) to a rise in the rate of output, unless, possibly, one is able to make the seemingly unreasonable assumption that labor should not appear in the production function.

The results would seem to imply that the economy exhibits constant or slightly decreasing returns to scale (mean returns to scale = 0.990, standard deviation = 0.0159). We should emphasize here that the data refer to the years 1929, 1940, 1941, and 1947-1969. It is possible that extension of these data into the past or the years after 1969 could alter these results. Data on the post-oil embargo years would be interesting but it seems very unlikely that any change that showed up in the results would be significant, considering the weight of the evidence presented here.

An alternative view of the production process is possible which contains more physical meaning. We could consider labor and capital as intermediate products and energy (more broadly, availability) as the single contributing factor to production. Availability is the measure of an entity to do mechanical work. To do work, it is only necessary that this entity possess a greater degree of order than its environment.

Thus, of course, coal, oil, gas and uranium possess a calculable amount of availability and so does iron ore, geothermal energy, solar radiation, rain, wind, etc. In any time period, these physical factors combine under the guidance of man (technology) and nature to allow the production of labor and capital and subsequently the production of our desired goods and services. Availability occurs in two forms. A flow of sunlight and geothermal energy and a stock of fossil and nuclear fuels and a stock of non-energy minerals such as iron ore, bauxite, etc. There is also an enormous amount of order stored in the earth, water and air, but their availability is very low on the average.

Joyce estimated the availability in the non-fuel minerals mined in 1968 at about 1.0 quads. A very rough estimate of the photosynthesized solar energy harvested in this year is 5.0 quads, while the fossil and nuclear fuels and hydropower consumed was about 70 quads. The dominant consumption of availability was clearly from the stock. An interesting future project will be a statistical analysis of the historic trend in GNP, technological change and the consumption of availability. If such a view of the macro economy has meaning then to the extent that availability flows can be substituted for stocks, the output of the economy can be preserved.

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ACKNOWLEDGEMENT - We wish to thank Andrew Postlewaite, Department of Economics Princeton, and Robert Solow, Department of Economics, Massachusetts Institute of Technology, for their many useful comments.